Astron. Astrophys. 287, 843–851 (1994)

NASA-CR-203592

ASTRONOMY AND ASTROPHYSICS

Spatially resolved X-ray and radio observations of Castor A+B+C

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Received 28 September 1993 / Accepted 4 January 1994

Abstract. We report on non-simultaneous X-ray (with the ROSAT HRI and PSPC) and radio observations (with the VLA) of the visual binary α Gem (= Castor A+B). Each component of this visual binary system is itself spectroscopic, with an A-type star as primary component. In our radio maps we clearly detect a source at the position of Castor A, but not at Castor B. Our X-ray observations confirm the previous detection of X-ray emission from the Castor A+B system, and indicate that Castor A, i.e., the radio source, is also the likely site of the X-ray emission. We examine in detail the hypothesis that both the X-ray and radio emission from Castor A come from the presumably late-type secondary, and show that this hypothesis encounters difficulties. If radio and X-ray emission came from the A-type primary, α Gem A would be one of the nearest X-ray and radio emitting A-type stars.

Key words: X-rays: stars – stars: coronae – radio continuum: stars – stars: α Gem – binaries: visual, spectroscopic

1. Introduction

The system Castor A+B+C is a somewhat unusual multiple system. First of all it contains three visual stars. The two brightest stars, i.e., the components A and B with magnitudes $m_{v,A}$ = 1.95 and $m_{v,B}$ = 2.85 and spectral types A1V and A5Vm form a visual binary with a semimajor axis of 6.8" (Heintz 1988); the actual angular separation varies between 1" and 6.8" depending on orbital phase ($P_{orb} \sim 467$ years). The two components constitute the bright star α Gem. An optically much fainter component Castor C, also known as YY Gem ($m_{v,C} \approx 9$), is located 71" south of Castor A+B and forms a proper motion pair with α Gem. The remarkable fact about this triple system is that each of the three visual components is a spectroscopic binary, so that the whole system consists of six stars.

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The system Castor A has a period of 9.21 days with an eccentric orbit, while Castor B has a period of 2.93 days in a synchronous orbit. It is sometimes claimed (cf., Burnham 1978) that all of the four stars in Castor A and B are A-type stars; however, we have not been able to find proof for this claim in the literature. At any rate, for the last decades the system was extremely difficult to study optically because of the close proximity of the two components; at present their angular separation is 3.2" as compared to 1.9" in 1969.

The system Castor C (= YY Gem) with a period of 0.814 days has been extensively studied in a variety of wavelength bands. Since YY Gem is a spectroscopic and eclipsing binary, stellar masses and radii could be determined; the system contains two almost identical M dwarfs with masses and radii of 0.57 $M_\odot$ and 0.62 $R_\odot$, respectively. From the point of view of magnetic activity, YY Gem is interesting because the tidally enforced rapid rotation is expected to lead to high levels of activity. Indeed, using the *Einstein Observatory*, Golub et al. (1983) were able to detect X-ray emission from the Castor A+B+C system; from the positional coincidence of the X-ray source with YY Gem, Golub et al. (1983) argued that all of the X-ray emission from this system should come from YY Gem rather than α Gem.

Extensive studies of YY Gem were carried out with the EXOSAT Observatory. Somewhat surprisingly, Pallavicini et al. (1990) detected quiescent and flaring X-ray emission not only from YY Gem, but also from the system α Gem, which had hitherto been believed to be X-ray dark. A reanalysis of the *Einstein Observatory* data (using a more sophisticated source detection algorithm) by Pallavicini et al. (1990) showed that X-ray emission from α Gem was also present in the *Einstein Observatory* observation at essentially the same ratio of flux levels as present during the EXOSAT observations.

This finding is unexpected because A-type stars are commonly thought to be X-ray dark (cf., Schmitt et al. 1985) due to the absence of convective outer layers which are thought necessary to produce an efficient magnetic dynamo (and thus solar-like coronae) as well as due to the absence of massive radiatively driven winds, whose instability leads to shock production with ensuing X-ray emission. While this view has been supported by observations with the *Einstein Observatory* and has now been confirmed by deep ROSAT pointings on selected nearby single A-type stars (Schmitt 1994), recent ROSAT observations of visual binary pairs containing an early type star and a post T-Tauri star showed evidence for (unexpected) X-ray emission from at least some of the early type components (cf., Schmitt et al. 1993). Consequently, it is essential to provide a number of well-documented cases for X-ray emission from A-type stars; with such a data base at hand, it will be possible to decide whether (at least some types of) A-stars should be considered as a class of X-ray emitters by themselves.

At microwave wavelengths we are faced with a similar situation. This is of course not unexpected, since both microwave emission and X-ray radiation are thought to originate from magnetic coronal loops. While the X-ray emission comes from thermal plasma and thus derives its energy from the (unknown) coronal heating process(es), microwaves from active stars are usually interpreted as radiation from a tenuous population of accelerated, mildly relativistic particles; if the radiation is broad-band and not very strongly polarized, this emission is most probably gyrosynchrotron emission produced by electrons spiralling in magnetic fields. Thus in active stars, both coronal heating and particle acceleration may be by-products of the same, possibly flare-like energy releases. Consequently, A-type stars are also expected to be microwave-dark, and this view is supported by a clear deficiency of microwave detections even among the nearest candidates. An interesting exception is the class of chemically peculiar Ap stars which has been found to comprise very luminous microwave sources (e.g., Drake et al. 1987); some of these stars have been detected, not too surprisingly, as strong X-ray sources as well (Cash & Snow 1982; Drake et al. 1994). The origin of the very strong magnetic fields on these stars still awaits theoretical explanations. Our target Castor A+B has, to our knowledge, not been detected at microwave wavelengths before.

As far as α Gem is concerned, its X-ray emission can be explained by ascribing the emission to a faint optical component which is in fact the interpretation given by Pallavicini et al. (1990) to account for the observed X-ray emission from α Gem. While such late-type companions can essentially never be fully excluded (even the Sun is sometimes suspected to have an hitherto undiscovered companion star !), a more interesting and – from the point of view of the recent ROSAT observations – possibly more plausible hypothesis would be to presume that the emission comes from one or both optical primaries; such a scenario could then be tested by studying both X-ray and microwave emissions from α Gem and comparing them with the well-studied behavior of late-type main-sequence stars.

With this in mind, we have carried out (non-simultaneous) observations of the Castor A+B+C system with the ROSAT HRI and PSPC at soft X-ray wavelengths and with the Very Large Array (VLA)[1] in microwaves in order to address the following questions: i) Which of the components in the Castor system are X-ray and/or microwave sources, and can therefore be regarded as candidate stars with active coronae? ii) How does the activity compare with later-type stars, which have been observed and detected both at X-ray and microwave wavelengths? iii) Is the activity similar on Castor A+B and Castor C, given their (presumably) similar ages? In this paper we present the ROSAT and VLA observations and discuss the implications of our measurements for the origin of activity in the Castor system. In Sect. 2 we will discuss our new ROSAT HRI and PSPC observations as well as the VLA observations of the Castor system; in Sect. 3 we present our astrometrical studies, and Sect. 4 contains a discussion of the results and our conclusions.

[1] The VLA is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under cooperative agreement with the U.S. National Science Foundation.

2. Observations

2.1. *ROSAT observations*

The X-ray data reported here were obtained with the ROSAT High Resolution Imager (HRI) between April, 18, 1992, 19:15 UT and April, 19, 1992, 00:33 UT in four individual observing intervals of approximately 1000 seconds each; the total accepted image time was 4073 seconds. The HRI is a microchannel plate detector which provides high resolution imaging with the on-axis point response being of the order $\sim 5''$. The spectral resolution of this device is rather modest, and essentially allows only a discrimination between very soft X-ray spectra (in particular through UV leakage) and hard X-ray spectra; an extensive description of the HRI detector used for this observation has been given by David et al. (1992). We will also present observations of the Castor A+B+C system obtained with the ROSAT position sensitive proportional counter (PSPC); these data were obtained in the period between March 29, 1991 and April, 4, 1991. The positional resolution of the PSPC depends on the measured pulse heights of the X-ray events; while at the softest X-ray wavelengths the point spread functions of Castor C and Castor A+B significantly overlap, the angular distance of $\approx 71''$ is large enough to allow a clear separation at higher pulse height channels (see Fig. 1b).

The attitude reconstruction of ROSAT data is accomplished through simultaneous measurements of optical stars with a star sensor (which in fact is tilted with respect to the optical axis of the X-ray telescope). While in principle X-ray positions can be measured arbitrarily well (since the statistical position error decreases as $N_{phot}^{-1/2}$ with N_{phot} denoting the number of available source photons), one is in practice limited by systematic errors. A comparison of the difference between optical and X-ray positions of a large sample of X-ray sources with well known optical positions shows a boresight offset (which can be removed), in addition to a dispersion around the mean of about 6" (Kürster 1993); the reason for this rather large dispersion is not precisely known, but very likely caused by an incorrect correction of pixel-to-pixel variations in the star sensor. As a consequence, **absolute** ROSAT positions may be incorrect by a couple of arcseconds (even for data with very good counting statistics), and the point response function in an integrated X-ray image of-

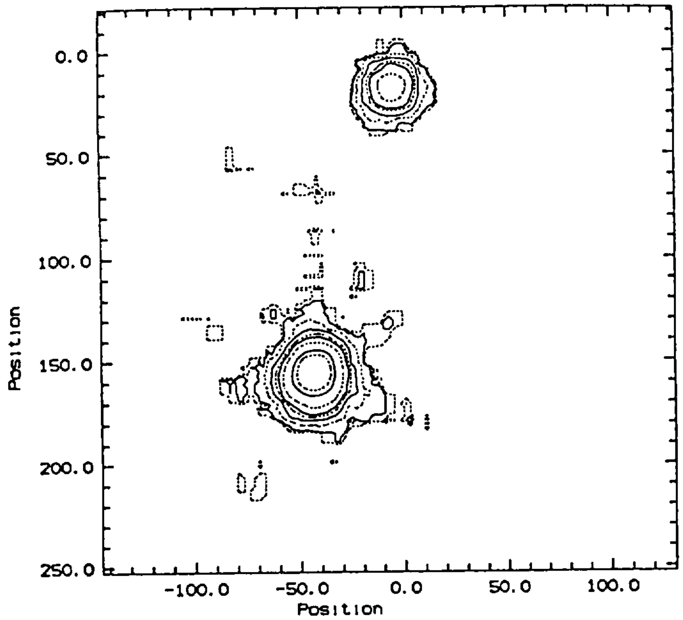

Fig. 1a. ROSAT HRI map of the Castor system. The two sources are YY Gem (to the South) and α Gem to the Northeast

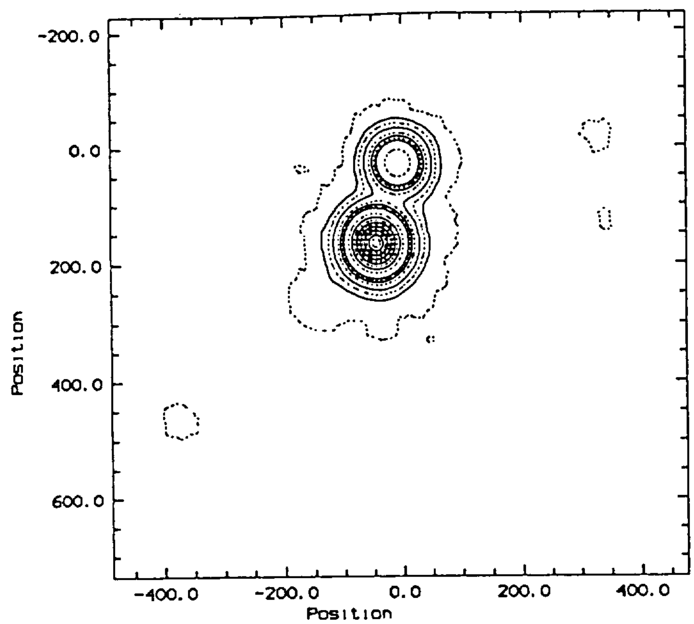

Fig. 1b. ROSAT PSPC map of the Castor system; only the pulse height channels above 50 have been used in order to utilise the better spatial resolution of the ROSAT PSPC at higher energies. The two strong sources visible near the center are YY Gem (to the South) and α Gem to the Northeast

ten does not appear symmetric but elongated. However, if one constructs images over short time intervals, the point response function becomes symmetric, and therefore the elongation in the integrated image is caused by an apparent residual motion of the X-ray source on the sky. If one is dealing with a (point) source strong enough that the X-ray position can be reliably determined with, say, a 20 second integration, this residual motion can be corrected for ("de-speckling").

As far as Castor A+B is concerned, it is of course next to impossible to directly resolve the A and B components spatially, given their angular separation of 3.1" at the time of our observations. Further, given the aspect uncertainties of our ROSAT data, it is also not possible to infer from positional coincidence which component is the actual X-ray emitter. However, since YY Gem, a rather strong X-ray source, is so close to α Gem, we can determine the **relative** position of Castor A+B with respect to YY Gem. This relative position should be free of all systematic aspect uncertainties; however, in order to obtain the best possible relative position, the image needs to be de-speckled. We therefore determined the apparent X-ray position (i.e., right ascension R.A. and declination δ) for YY Gem with 20 second integrations as a function of observing time, fitted a spline curve through these data points, and then corrected all recorded photons with the appropriate time-dependent correction in R.A. and δ.

The image obtained with this de-speckle procedure is shown in Fig. 1a. Two X-ray sources are clearly seen, the strong source in the center of Fig. 1a is YY Gem, the source to the Northeast is α Gem. The ROSAT HRI is known to have some UV sensitivity. Extrapolating the UV count rate observed from the nearby star Vega, i.e., 0.07 cts/s, to that appropriate for Castor A+B by scaling by the ratio of the B magnitudes of the stars, we find an expected UV count rate of ≈ 0.004 cts/s, which is much less than the observed count rate of 0.22 cts/s. The observed signal is thus clearly due to X-rays, and therefore we can fully confirm the conclusions by Pallavicini et al. (1990) on the quiescent X-ray emission from α Gem.

As far as the total measured energy flux and by implication the total luminosity in the measured X-ray band are concerned, they do of course depend on the assumed incident photon spectrum; the lack of spectral resolution of the HRI does not allow us to study temperatures of the emitting plasma, while a spectral modelling of the PSPC pulse height data is complicated by the fact that in the soft energy channels the photon events received from α Gem and YY Gem overlap. In the higher energy channels however α Gem and YY Gem are clearly separated, and an image of the PSPC data is shown in Fig. 1b. Therefore the PSPC spectrum of α Gem must be quite hard and in fact similar to YY Gem. Using an energy conversion factor of 3 10^{-11} erg/cm^2/count between flux (in cgs units) and HRI count rate, we find an X-ray luminosity of $\log L_X \approx 29.2$ in the ROSAT band, which places the α Gem X-ray source near the top end of the observed X-ray luminosity range for coronal sources (except RS CVn systems and (post) T Tauri systems).

2.2. *VLA observations*

The radio observations described here were obtained with the VLA on October 14 and 19, 1991, at the four wavelengths of 2 cm (14.5 GHz), 3.6 cm (8.5 GHz), 6 cm (4.9 GHz), and 20 cm (1.4 GHz) in A/B array configuration; we used the full array for observations at one frequency at a time, and switched

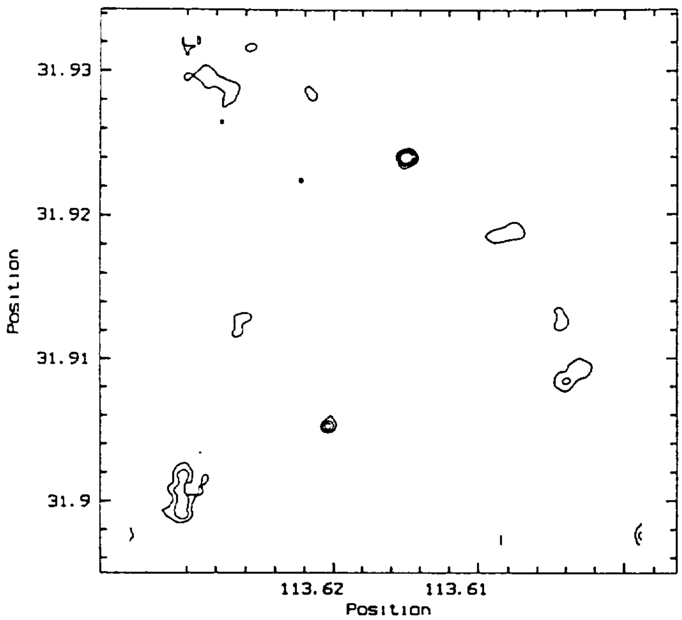

Fig. 2a. VLA 20cm map of the Castor system. The two sources shown are YY Gem (to the South) and α Gem to the Northeast

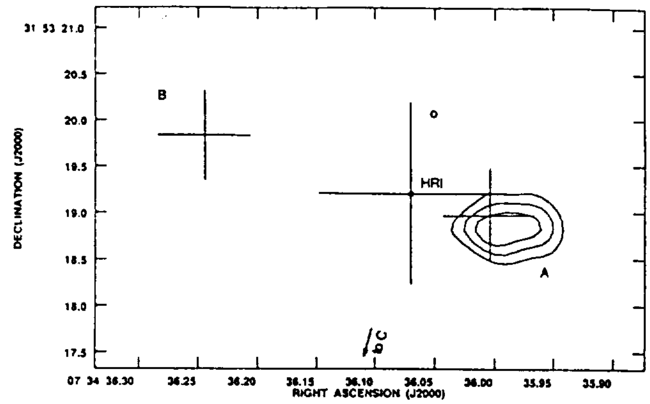

Fig. 2b. Sketch illustrating the J2000 positions of our Castor observations. The contours represent the VLA 6 cm detection of October 19, 1991, with contours separated by one σ, the lowest being at 3σ above background (σ = 0.036 mJy). Notice that the FWHM of this stellar image is about three times narrower than the 20 cm contour image in Fig. 2a. We further notice that this particular 6 cm detection tends to be slightly but insignificantly (0.12") *west* of the averaged VLA position which is precisely at the optical R.A. The two smaller crosses define the optical catalog positions of Castor A (right) and B (left), the length of the error bars giving an estimate of the uncertainty in absolute position. The large cross defines the position of the centroid of the ROSAT HRI observation, interpolated between the *optical* positions of Castor A and B according to the corrected position angles with respect to YY Gem (text after Eq. 6, and Eq. 7). We have assumed that the radial distance between Castor and YY Gem in the HRI image corresponds to the true distance, as derived in Eq. 6a–d. The open circle to the north of the HRI position defines the HRI centroid if this assumption were not made, i.e. assuming the relative distance as given in Eq. 7. The deviation yields an estimate for the systematic errors in the HRI position of $\approx$1", illustrated by the large error bars

between the four frequencies in steps of the order of ten minutes. The total bandwidth was 100 MHz at all frequencies. The full data set was obtained during 7 consecutive hours on the first date, and during 4.5 consecutive hours on the second date. We included observations of a phase calibrator at regular intervals, and obtained flux calibration by observing the calibrator 0134+329 = 3C48. The wide array configuration allowed us to obtain optimum spatial resolution; the FWHM of the beam was approximately 0.25, 0.36, 0.65, and 1.9 arcsec at our four observing frequencies in north-south direction and about twice as much in east-west direction for the four wavelength bands, respectively. All data sets were calibrated and mapped using standard AIPS software. Field sources were cleaned and their clean components subtracted from the data base. This was especially important on the 20 cm maps, which contained about ten sources at fluxes above 1 mJy whose sidelobes strongly "contaminated" our maps. As an example we show the cleaned 20 cm VLA map obtained on October 14, 1991 (cf., Fig. 2a): note that the scale of Fig. 2a is identical to that of Fig. 1. The two sources visible are YY Gem (to the South) and a source near α Gem (to the Northeast).

The cleaned images were analyzed with different statistical AIPS tasks like IMFIT, JMFIT, or IMEAN to determine precise positions and fluxes. The first two procedures fit two-dimensional Gaussian functions to the cleaned stellar images, which effectively permits a determination of centroid coordinates at higher precision than the nominal angular resolution in the data. Once the stars were detected and identified on the maps, we could thus determine their position with an accuracy at least ten times smaller than the distance between the two components Castor A and B. Since the absolute positions of these stars are well known and the internal positional error in VLA positions is of the order of 0.1", we can unambiguously identify any of the three (visual) binaries in the Castor system. Furthermore, since the measured VLA coordinates of YY Gem = Castor C are likely to be more precise than most catalog positions, we can obtain relative coordinates between Castor C and any of the components in Castor A+B with an accuracy of the order of 0.1-0.2 arcsec, and determine position angles with an accuracy of about 0.2 degrees.

The dMe binary Castor C was detected at all four frequencies at flux levels similar to or somewhat lower than those reported in previous observations (e.g., Gary & Linsky 1981; Gary 1985, 1986). The YY Gem system shows a somewhat peculiar microwave spectrum in the sense that the spectral index is either positive or very close to zero up to 14 GHz. In Table 1 we summarise the total fluxes as measured on our whole time maps. Both spectra increase from 20 cm to 6 cm or 3.6 cm, and then seem to flatten. Similar spectra of this system were presented by Gary (1985), while the more typical dMe microwave spectra show a spectral peak at low frequencies ($\sim$1–5 GHz), and then fall off towards higher frequencies (e.g., Güdel 1994; Güdel & Benz 1994).

Surprisingly, our maps showed a relatively strong microwave source at the position of the Castor A+B system as

Table 1. Microwave fluxes measured by the VLA

frequency (GHz)	flux YY Gem (mJy)	flux Castor A (mJy)
October 14, 1991:		
1.4	0.43±0.039	0.62±0.037
4.9	0.47±0.023	< 0.075
8.5	0.54±0.024	< 0.069
14.5	0.57±0.051	< 0.16
October 19, 1991:		
1.4	0.30±0.044	0.48±0.045
4.9	0.51±0.038	0.19±0.036
8.5	0.41±0.034	0.13±0.032
14.5	0.47±0.067	< 0.19

well. The source was especially prominent in the 20 cm maps on both days, but was also detected at higher frequencies. Only one of the two binary components, Castor A, was positively detected; we discuss the positional identification process in the next section. Here, we briefly summarize the emission properties reported in Table 1: i) The overall flux level of Castor A is comparable to YY Gem, though it exceeds the latter by a factor of $\sim$1.5 at 20 cm wavelength. ii) The microwave spectrum is variable; on October 14, the spectrum was very steep, resulting in a non-detection with rather low upper limits at 4.9 GHz and above. The spectral index between 1.4 and 4.9 GHz was thus $\lesssim -1.7$. The spectrum became much flatter on October 19, so that the star was detected both at 4.9 and 8.5 GHz despite the lower 1.4 GHz flux level. The spectral indices were -0.74 and -0.69 in the intervals 1.4–4.9 GHz and 4.9–8.5 GHz, respectively. iii) Although very weak signals at the 3–3.5σ level were found at 14 GHz at the same position, we do not consider those to be reliable detections. Such a marginal detection is especially suspect in the case of the Oct. 14 observations, which did not yield a positive signal in the two intermediate bands. iv) The 20 cm images were slightly polarized at the $\sim$30% level; we caution that some polarization can be introduced by the off-center position of the Castor system on these maps, though the expected level of additional polarization at the position of Castor (radial distance from phase center $\approx$ 4% of the primary beam at 20 cm wavelength) is a few percent only (Cornwell 1993).

The high signal to noise ratio in the 20 cm observations allowed us to study temporal variability. We made cleaned maps for the seven 10 minute scans that were separated by about one hour each, and determined fluxes using the same methods as before. The increased noise in these maps made the application of some of the AIPS flux determination and fitting routines less reliable, though from a comparison of different methods, we conclude the following: i) The 20 cm flux is slowly variable on time scales of about one hour (we were unable to identify any variations on shorter time scales). ii) Fluxes varied between 0.3 and 1.2 mJy on Oct. 14, and between 0.3 and 0.7 mJy on Oct. 19, with a 1σ rms of about 0.10–0.12 mJy.

In order to study the behavior of Castor's radio emission further, we checked additional VLA observations that were available to us; they were obtained in phased array mode during intercontinental VLBI sessions on YY Gem, with some of these observations being rather close in time to those reported above. The VLBI and phased array VLA observations are described in detail by Benz et al. (1994). We did find possible detections of Castor A on one or two of these maps, although the rather weak signal-to-noise ratio at best allows us to make a preliminary statement on the reality of Castor A's long-term microwave activity, and on the variability of this star. Some of these maps had rather high noise rms values due to considerable interference problems at the 18 cm observing frequency, and due to the narrower continuum bandwidth during VLBI sessions (50 MHz as compared to 100 MHz for the observations presented above). The relevant observations are:

- An 18 cm observation obtained on September 26, 1991 (A/B array), with a 3.1σ detection of 0.244±0.078 mJy at a position of R.A.(2000) = 7^h 34^m 36.014^s, δ(2000) = 31° 53' 18.51", with no measurable polarization. This position closely agrees with the one for the observations reported in this paper (see Eq. 4 below).
- An 18 cm observation obtained on September 28, 1991 (A/B array), with a possible, though not significant signal of 0.218±0.089 mJy ($\approx 2.5\sigma$) at about the same position, R.A.(2000) = 7^h 34^m 35.921^s, δ(2000) = 31° 53' 18.81"; the low signal-to-noise ratio and a rather elongated and somewhat distorted stellar image make this detection ambiguous.
- To clarify the reality of the previous two signals, we co-added all visibilities relevant for the two observations; we now find a source with a total flux of 0.234±0.061 mJy at R.A.(2000) = 7^h 34^m 35.990^s, δ(2000) = 31° 53' 18.51" (no significant polarization measured, with flux in Stokes V $\lesssim$ 0.162 mJy); the deviation of this 3.8σ detection from the clear detection of our present observations is an insignificant 0.39". The improved signal-to-noise ratio further suggests that weak emission at this level was present on both days at 18 cm.
- An observation at 6 cm on September 21, 1991 (A/B array), yielded no detection, with a 3σ upper limit of 0.14 mJy.
- An observation at 18 cm on March 15, 1990 (in A array), resulted again in no detection, with a rough 3σ upper limit of 0.78 mJy.

We notice that the 6 cm upper limit on Sept. 21, 1991, is in agreement with the average of the 6 cm observations reported for the October observations and therefore does not yield additional constraints for variability. The 18 cm observations on Sept. 26 and 28 suggest that the 20 cm detections in October 1991 were exceptionally high; it is conceivable that part of the relatively high 20 cm flux and its polarization are due to additional, superimposed coherent (flare) emission as is often observed on late-type stars at this wavelength; while this would also naturally explain the rather steep spectrum observed on October 14, 1991, we do not have additional evidence to further support this assumption.

Could the variation of the 18–20 cm fluxes during September-October 1991 be related to the orbital phase of the eccentric Castor A binary system? Defining phase = 0 for the center of the September 26, 1991, observation, the relative orbit phases for the September 28, October 14, and October 19 observations are, respectively, 0.22, 0.96, and 0.51. High fluxes were thus observed at phase 0.51 and 0.96, while fluxes were at a low but comparable level at phases 0 and 0.22. We therefore do not find a solid argument in terms of a coupling with orbital phase.

3. Astrometry

Clearly, the active M binary system YY Gem was detected with both the ROSAT HRI and the VLA, but which one of the two components of α Gem do we see ? We will first identify the VLA source based on its absolute coordinates, then, with updated coordinate values, calculate distances and position angles between the system components, and finally try to identify the X-ray source.

3.1. Castor A+B+C at optical wavelengths

We have searched the literature for orbital elements of the Castor A+B system; we decided to use the elements given by Heintz (1988), who also reports the total masses of the Castor A and the Castor B system ($M_A = 2.1 M_\odot, M_B = 1.6 M_\odot$). At the time of our VLA observations (epoch 1991.786), we find a separation (between A and B components) of 3.17" at a position angle of 74.65 degrees. From Fricke et al. (1988) we can determine the equinox 2000 position of the center of gravity (c.g.):

Castor c.g. (Epoch 1991.786)

$$RA(2000) = 7^h\ 34^m\ 36.108^s \qquad \delta(2000) = 31^\circ\ 53'\ 19.34'' \tag{1a}$$

From the offsets of the A and B components with respect to the c.g. position (using the position angle, the distance, and the mass ratio as given by Heintz 1988) we then find

Castor A (Epoch 1991.786)

$$RA(2000) = 7^h\ 34^m\ 36.004^s \qquad \delta(2000) = 31^\circ\ 53'\ 18.98'' \tag{1b}$$

Castor B (Epoch 1991.786)

$$RA(2000) = 7^h\ 34^m\ 36.244^s \qquad \delta(2000) = 31^\circ\ 53'\ 19.82''. \tag{1c}$$

The relative positions of the c.g. of Castor A+B and Castor C = YY Gem can be derived from expressions determined by Heintz (1988)

$$\Delta(\alpha) = 18.831 - 2.347\,T \quad (arcsec) \tag{2a}$$

$$\Delta(\delta) = -68.429 + 0.362\,T \quad (arcsec); \tag{2b}$$

here T denotes the epoch in terms of centuries since the year 2000. Using these expressions and Eq. (1a), we find the coordinates of YY Gem as

Castor C (Epoch 1991.786)

$$RA(2000) = 7^h\ 34^m\ 37.602^s \qquad \delta(2000) = 31^\circ\ 52'\ 10.88'' \tag{3}$$

3.2. Castor A+B+C at radio wavelengths

We measured the position of the radio source near Castor A+B on our VLA maps as

VLA source (Epoch 1991.786)

$$RA(2000) = 7^h\ 34^m\ 36.006^s \qquad \delta(2000) = 31^\circ\ 53'\ 18.84''. \tag{4}$$

These are the averages of four observations (Table 1); relevant for us will be the statistical scatter in right ascension, which amounts to 0.21". Comparing optical and radio positions unambiguously identifies our VLA source with Castor A, with a positional deviation of only 0.14" (in declination); this is compatible with the estimated errors in the VLA positions. For completeness, we also give the VLA coordinates of YY Gem for Epoch 1991.786, as averaged from the 3.6 cm and 2 cm maps:

VLA Castor C (Epoch 1991.786)

$$RA(2000) = 7^h\ 34^m\ 37.584^s \qquad \delta(2000) = 31^\circ\ 52'\ 10.98'' \tag{5}$$

Evaluating now the expression (2) at the time of our observation, we find the relative distance between the center of gravity or Castor A or Castor B on one hand and YY Gem on the other hand:

$$r_{cg-YYGem} = 71.05'', \text{position angle } 164.47^\circ \tag{6a}$$

$$r_{A-YYGem} = 71.07'', \text{position angle } 163.37^\circ \tag{6b}$$

$$r_{B-YYGem} = 71.07'', \text{position angle } 165.92^\circ \tag{6c}$$

To suppress even slight systematic effects in the relative VLA positions, we obtained position angles and distances separately from the three better maps; the averages are

$$r_{source-YYGem} = 70.84'', \text{position angle } 163.54^\circ \tag{6d}$$

again clearly supporting the view that the VLA source is indeed Castor A. Having thus identified the microwave source near the Castor A+B system, we suggest to adopt the VLA coordinates for Castor A and Castor C = YY Gem, due to their rather small uncertainty of the order of 0.1" (better than typical catalog positions for faint stars); this also defines a consistent set of coordinates. Thus, we will adopt position angles that are 163.54 – 163.37 = 0.17 degrees larger than those reported in Eq. (6a-c), i.e., we will replace those values by 164.64, 163.54, and 166.09 degrees, respectively.

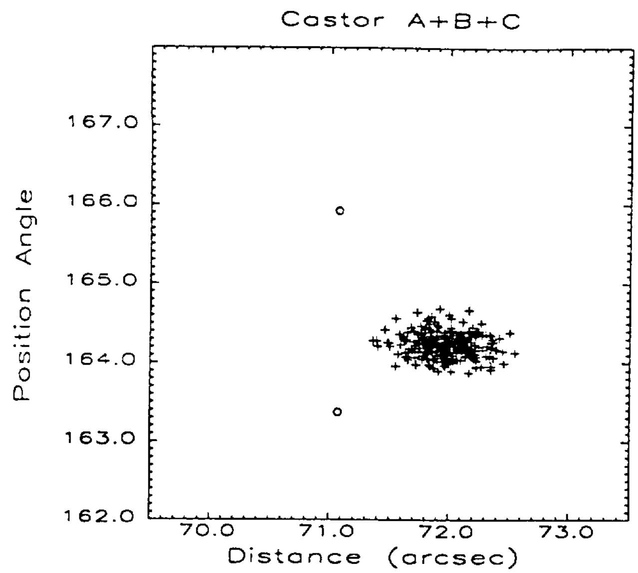

Fig. 3. Statistical uncertainty of the relative HRI position of the α Gem X-ray source, expressed in terms of radial distance and position angle with respect to YY Gem; the individual points represent the result of 300 Monte Carlo simulations. The two circles represent the relative positions of Castor B (top) and Castor A (bottom); note that the cloud of points lies well away from the two nominal positions, indicating that systematic errors dominate

3.3. Castor A+B+C at X-ray wavelengths

We will now use the distances and position angles derived above to estimate which components were detected by the ROSAT HRI. Since the VLA and ROSAT observations were taken only six months apart, there is no need to correct the relative coordinates (distance, position angles) between any two stars due to differential proper motion (see Eq. 2, and consider orbit period of 467 years for the A+B system). In order to avoid confusion because of the UV contamination of the HRI (cf., Sect. 2.1), we decided to use only the pulse height channels above channel 4 (where UV induced signals are absent) for the subsequent analysis. We ran a maximum likelihood (ML) source detection on the "de-speckled" image and determined the image coordinates for both X-ray sources; note that the absolute coordinates cannot be used because of the possible systematic errors in ROSAT positions. On calculating the distance and position angle between YY Gem and the X-ray source near α Gem, we find the nominal values

$$r_{X-ray\ source-YYGem} = 71.98'', \text{position angle } 164.24^{\circ}. \quad (7)$$

In order to assess the errors in the above values (the image derived coordinates for YY Gem and α Gem have different errors because of the different count statistics) we performed a Monte Carlo simulation based on the calculated ML errors for the image coordinates. The results of these simulations are shown in Fig. 3 as a scatter plot of relative source distance r vs. position angle p.

Both from Eq. (7) as well as the error distribution shown in Fig. 3 it is suggestive to interpret the X-ray source – just like the radio source – as Castor A and not as Castor B. As is clear from Eq. (6), the relative distances between Castor C and Castor A and B, respectively, are virtually identical, the only difference being in position angle; the X-ray position angle of 164.24° fits much better to the (VLA) position angle of 163.54° of Castor A rather than that of Castor B. On the other hand, the angular distance of 71.98" between the two X-ray sources is 1 arcsec too large **regardless** of the identification with Castor A or B, indicating that systematic errors actually dominate the statistical errors we have dealt with via Monte Carlo simulations. The deviation in position angle between Castor A and the X-ray source (with respect to YY Gem) is about 0.7 degrees, comparable with the scatter in position angle displayed in Fig. 3. This angular deviation translates into a azimuthal deviation of only 0.87" at Castor's relative distance of 71"; this deviation is thus *smaller* than the systematic error in radial distance, in agreement with our identification of the X-ray source with Castor A. Notice, on the other hand, that the azimuthal deviation between the X-ray source and Castor B is, as seen from YY Gem, approximately 1.9 degrees corresponding to an offset of 2.3" (Fig. 2b).

4. Discussion and conclusions

Our ROSAT HRI and VLA observations of the Castor A+B+C system have clearly detected the active M dwarf binary Castor C at the anticipated flux levels at X-ray and microwave wavelengths; additionally, we find a similarly strong source in both wavelength regimes close to the Castor A+B (= α Gem) system. Since the optical primaries of Castor A and B are both of spectral type A and are thus expected to be neither X-ray nor microwave-strong, this observation is of particular interest.

Using precise orbital elements for the Castor A+B system and coordinates of the center of gravity, we have **unambiguously** identified the microwave source near α Gem as Castor A, while we did not detect any microwave emission from Castor B with stringent upper limits (see Table 1 for rms figures). Using the coordinates as determined from our VLA observations, we attempted to identify the ROSAT HRI source based on relative coordinates. While the X-ray data are not as unambiguous as the radio data, we argue that the detected X-ray source is also identical with Castor A for the following reasons: i) Using the harder HRI channels, we find that the position angle between the centroid positions of YY Gem and the α Gem source is closer to Castor A (cf., Fig. 3); the deviation from the expected position is within the adopted systematic error as found in radial distance ($\lesssim$ 1"), and favorably agrees with Monte Carlo simulations of the X-ray image. Only upon using the softer energy channels is the source centroid shifted slightly toward Castor B, which is reasonable since we expect similar UV contamination from both sources. ii) It appears quite unlikely to us that one of the binary components of α Gem is a microwave-dark but an X-ray-bright source, while the other is microwave-bright and X-ray-dark; if this were the case, one component would have to be surrounded by a hot corona, while the other component would possess no considerable hot corona but still exhibit strong magnetic activity, presumably in the form of particle acceleration to produce the observed synchrotron radio emission. iii) The observed PSPC light curve of α Gem (cf., Fig. 4) shows no periodicity with the 2.93 day orbital period of Castor B. While admittedly each of our three arguments is inconclusive by itself, we feel that the totality of our arguments provides strong support for the identification of the X-ray and microwave source with Castor A. This conclusion appears surprising from hindsight, since *a priori* one would have argued for Castor B as the more likely site of an active star system: With an orbital period of 2.93 days, synchronous rotation (as suggested by the absence of measurable orbit eccentricity), and the "later" spectral type among the two optical sources, one has all the required ingredients, while Castor A has a longer period and is very likely not synchronised.

As far as the relationship between X-ray and microwave emission is concerned, we know that on the Sun particle acceleration and coronal heating occur as by-products of the same magnetic energy release processes during flares; the measurable energy fluxes in X-rays and microwaves are correlated (Benz & Güdel 1993). Interestingly, this correlation is about the same as one that has been reported for "quiescent" radio and X-ray emission from late-type stars (Güdel et al. 1993; Güdel & Benz 1993), where radio emission is interpreted in terms of gyrosynchrotron emission from mildly relativistic electrons spiralling in magnetic fields. Since our 20 cm image of Castor showed some mild circular polarization and the emission was broad-band, the observed radio emission from Castor is with all likelihood gyrosynchrotron emission as well. Thus using the average 5–8.5 GHz luminosity observed for Castor A in the microwaves (i.e., $\log L_R \approx 13.6$) and the estimated X-ray luminosity ($\log L_X \approx 29.2$) based on the HRI count rate, i.e., 0.22 cts/s, we find a luminosity ratio of $L_X/L_R \approx 10^{15.6}$ Hz. This ratio is the same that we have previously found for other, later-type stars (cf., Güdel et al. 1993), and thus we obtain an additional suggestion that the radio and X-ray emission indeed originate from the same star, i.e., Castor A, while the other component, Castor B, does not seem to support detectable coronal activity. Of course, long-term variability remains to be investigated in this regard.

Accepting now that the X-ray and microwave source has been correctly identified with Castor A, the question arises, given the spectroscopic binary nature of Castor A itself, which one of the components is responsible for the observed activity ? Clearly, our data do not allow an unambiguous conclusion on this point. Ascribing the observed activity to a later-type star (say, early M) as done by Pallavicini et al. (1990), implies activity levels of similar magnitude as observed for the co-eval dMe binary Castor C, since the A-type, optical primary would then be assumed to be X-ray and microwave dark; note that *a priori*, YY Gem because of its binarity would expected to be twice as strong. While this is of course not implausible, it must be kept in mind that components of the Castor A system are likely to have a (much) longer rotation period (orbital period = 9.21 days, but non-zero eccentricity) than YY Gem ($P = P_{orb} = 0.814$ days, enforced by tidal interaction) and therefore exhibit less activity. Our observations are not conclusive: Both X-ray and radio (averaged 5-8.5 GHz) luminosities of Castor A are indeed smaller than YY Gem's by a factor of 5 and a factor of 4, respectively; further, the PSPC light curve of Castor A (cf., Fig. 4) shows the occurrence of flares as expected for a late-type star and thus confirms the findings of Pallavicini et al. (1990). Castor A's microwave *spectra*, on the other hand, are neither similar to YY Gem's nor to typical microwave spectra of other dMe stars, since they show, at least in our Oct. 14 observation, an unusually large negative spectral index above 1.4 GHz.

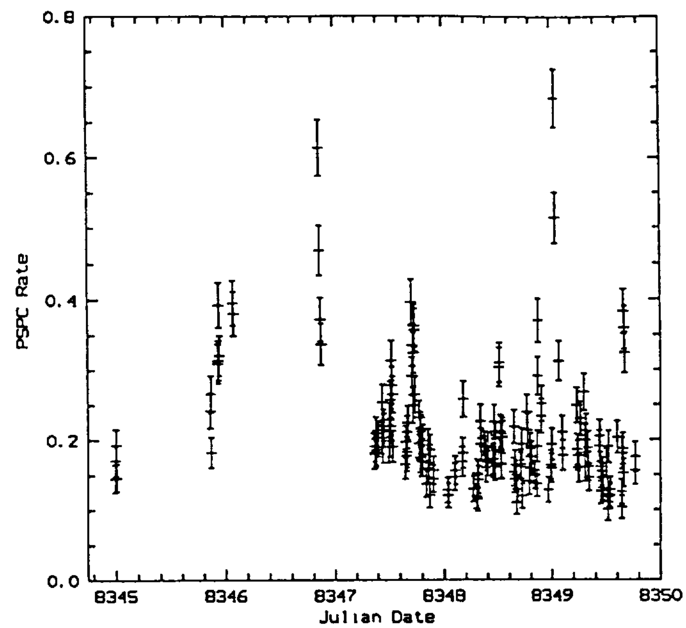

Fig. 4. ROSAT PSPC light curve of the α Gem X-ray source; only the photons above pulse height channel 50 and within 30 arcsec from the measured X-ray position are used in order to avoid spillover from the nearby YY Gem X-ray source

Ascribing the observed activity to a late-type active companion encounters further difficulties as far as the stellar masses of the individual components are concerned. For the Castor A system, Heintz (1988) determined a total mass of $2.1 M_\odot$, with a lower limit to the companion mass of $0.2 M_\odot$. With a resulting maximum mass of $1.9 M_\odot$, Castor A is undermassive given its spectral classification of A1V; for example, the well-determined mass of Sirius A (which has the same spectral type as Castor A) is 2.35 $M_\odot$! But if we have to assume a secondary near the minimum mass (i.e., 0.2 $M_\odot$), our observed X-ray luminosity would be larger than that observed for *all* other measured stars in the corresponding M_V range (cf., Fleming et al. 1993). Only M-dwarfs with masses of 0.4 - 0.6 $M_\odot$ or more (corresponding to spectral types around M0 or earlier) are routinely observed to exhibit X-ray emission levels similar to that of Castor A. Assuming therefore a secondary mass exceeding the lower limit will make the observed high level of X-ray luminosity less unusual, but will worsen the mass discrepancy, with a companion mass above $0.4 M_\odot$ resulting in an optical primary of spectral class F, contrary to observations. We conclude that any companion compatible with the optical spectral classification must be quite close to the lower mass limit of 0.2 $M_\odot$, while any companion consistent with the observed X-ray luminosity should have a mass of at least $\approx$ 0.4 $M_\odot$.

One way to possibly reconcile these conflicting mass estimates would be to assume that the parallax for the Castor system determined by Heintz (1988), who incidentally comments that Castor is a difficult system to measure, is incorrect. In Kepler's law $M_1 + M_2 = 4\pi^2 a^3/GP_{orb}^2$ (G being the gravitational constant) the total mass depends very sensitively on the semimajor axis a, which is derived using measured parallaxes. In fact, if one adopts the parallax quoted by Hoffleit (1982) or calculates the weighted mean of 9 parallax determinations taken from the SIMBAD database (references between 1952 and 1963), one finds p = 0.0667" (instead of p = 0.073" as adopted by Heintz 1988). With these values one then derives a total mass of the Castor A system of 2.75 $M_\odot$, which would in fact remove almost all of this "missing mass" problem. However, the problem with such an assumption is twofold: First, the value of p = 0.066" is smaller than the parallaxes quoted by Heintz (1988) for any of the three components of the Castor system (i.e., p = 0.0713" for Castor A, p = 0.0776" for Castor B, and p = 0.0924" for Castor C); and second, if Castor A were identical to Sirius A, we would, based on the apparent visual magnitudes, predict a parallax of p = 0.0786", which is much more consistent with the parallax determined by Heintz (1988). The parallax of p = 0.0667" would, if Castor and Sirius were equally bright, yield an apparent magnitude of 2.32, which appears to be inconsistent with its observed apparent magnitude of 1.95. If anything, Castor A appears to be of later spectral type and hence less luminous than Sirius A.

Another less conventional way to reconcile these seemingly conflicting findings would be to assume that in fact the X-ray emission from Castor A does not come from its somewhat elusive secondary, but from the primary A-type component. While it is true that almost all A-type stars in the solar neighborhood are X-ray dark (cf., Schmitt et al. 1985; Schmitt 1994; Schmitt & Kürster 1993), there are also examples of more distant but apparently X-ray bright late B-type or early A-type stars (cf., Schmitt et al. 1993). While in such cases one can – again – always argue that hitherto unseen low-mass companions are responsible for the X-ray emission, we wish to point out that the measured X-ray luminosity of Castor A is in fact in the X-ray luminosity range observed by Schmitt et al. (1993) in their sample of B- and A-type stars. Clearly, ascribing the X-ray emission to a star presumably without any convective envelope and without any radiatively driven wind causes problems for our understanding considerably more severe than the hypothesis that the X-ray emission comes from the late-type star.

At any rate, the discussion in the preceding paragraphs clearly shows that a redetermination of the spectral type and mass of Castor A is in order; the angular distance between the A and B components will grow larger during the next decades thus making optical observations easier. As far as X-ray observations are concerned, we expect no fundamental progress to be made until the High Resolution Camera onboard AXAF with its subarcsecond X-ray telescope (to be launched later in this millenium) will be able to resolve Castor A and B, and thus unambiguously locate the site of X-ray emission among the visual components of the α Gem system, and hence verify or falsify our conclusions.

Acknowledgements. We would like to thank our referee, Prof. Dr. R. Pallavicini, for his thoughtful review of our paper. MG acknowledges the hospitality of MPE during his visits. This work was supported by the Swiss National Science Foundation (grant 8220-033360) and by NASA through interagency transfer W-17,772 to the US National Institute for Standards and Technology. We also wish to point out that this research made use of the SIMBAD database, which is operated by CDS, Strasbourg, France.

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